Practical Testing of Grounding Systems by Current Injection

Tony Mitton BE (Elec) and Robin Watson BE(Hons) (Elec)

Mitton Consulting Ltd Christchurch New Zealand

Abstract:

This paper outlines practical methods for testing of grounding systems using current injection. Injection testing enables comprehensive testing of grounding systems. Many important grounding system parameters can be measured, including impedance, touch, step, and transferred voltages, ground potential rise contours, current splits in overhead ground wires, OPGW and cable screens. Injection testing is also suited to specific situations such as mining installations or power stations supplied by gas or oil. The latter cases require specific grounding measures for safety reasons and injection testing can confirm such issues. Injection testing also allows identification of any transferred voltages, for example, onto farm fences, water and gas pipelines, telecommunications and railway signalling circuits etc. Injection test methods can also be used to measure induced voltages into other services in a transmission line right-of-way.

1 Introduction

The ongoing reduction in price and increase in capability of power electronic technology has had significant implications for the electric power industry. One application in particular is the testing of power system grounding electrodes. In the past a variety of instruments and methods have been used to determine the adequacy of power system grounds. These methods are often based on simple resistance meter measurements incorporating significant assumptions about the environmental conditions in which the grounding system exists. To accurately test a grounding system required heavy current injection methods to swamp any power system noise. Now however, new portable power electronic test equipment is available that can accurately characterise a grounding system without the need for large and expensive equipment.

A key method enabled by this technology is the off-frequency low current injection testing and measurement method. Current at a frequency close to that of the power system is injected into the ground grid of any installation such as substations, transmission tower footings, distribution transformers etc. By injecting at a unique frequency, the test signals can easily be distinguished from background power system frequency noise and harmonics.

The current injection is from a remote location to simulate a real ground fault that will generally be supplied from remote sources. In this way the effects of overhead ground wires, induction, and cable screens are automatically included in the test measurements. From this, several key parameters of the grounding system can be determined that describe the performance of the grounding system.

First of all the grounding system impedance is measured in a way in which a ground fault would see it. This will enable power system calculations to accurately determine ground fault levels and the voltage rise of the ground grid. Secondly with the injection current established, touch and step voltage measurements can easily be made using voltmeters specifically tuned to the test frequency. Compared with conventional methods, the ability to use simple hand-held meters with short leads significantly increases freedom when locating potential touch and step voltage hazards.

The use of injection testing combined with computer modelling using software such as CDEGS™ enables the asset owner to gain an exact understanding of the grounding system. Results from site testing can be incorporated in the model or used to verify new designs. This means that a clear record of the grounding system performance is available. It also means that any changes to the grounding system can be easily included in a realistic model since the model is known to represent the actual grounding system.

2 Power System Grounding

The primary function of a grounding system is to provide a path for power system currents during short circuit conditions. This ensures that ground faults can be adequately detected and cleared by the protection equipment.

However, an unfortunate consequence of this is the creation of possible hazardous voltages during a ground fault. Significant voltages can be created when power system currents flow into the ground. These voltages can result in hazards to people and damage to equipment in the vicinity of the faulted installation. In addition to this, hazards can be transferred onto entire networks of conductors such as fencing, pipelines, and telecommunications circuits far away from the actual fault location.

The severity of the ground voltage rise and associated hazards are directly influenced by the effectiveness of the grounding grid. A key performance indicator is the grounding system impedance. High overall impedance relates to a greater ground grid voltage rise and subsequently higher touch and step voltages.

3 Requirement for Testing

The impedance of a grounding system needs to be measured for several reasons. Firstly, measurements help ensure that new ground grid designs are adequate. Computer modelling is a valuable tool for design but it is difficult to include all parameters which may affect the resultant ground grid characteristics. It is well accepted that "one test is worth 1,000 expert opinions".

Secondly, the performance of a ground grid, particularly of small size, is inherently susceptible to variations of the surrounding soil. To truly verify the performance, regular testing should be conducted to monitor the condition of the grounding system over time.

Subsequently a practical means of checking a grounding system is needed to ensure that a ground grid is operating correctly and that no voltage hazards exist both for people and equipment.

4 Grounding System Test Methods

There are currently a variety of methods available for testing grounding systems. These are generally based on either simple portable tester measurements or current injection methods. IEEE Standard 81 ([1], [2]) and other documents describe a number of these including:

- Simple two point and three point methods
- Fall-of-potential and related methods
- Power frequency current injection
- Off-frequency current injection

The simple resistance based techniques like the fall-of-potential method are desirable because small portable ground testers can be used. However, portable ground testers are not practical for measuring touch and step voltages because long tests leads are required between the ground grid, meter, and the test point. Also, in some situations portable testers may not work due to:

- Electrical noise on the ground grid from power system equipment.
- Very low grid impedance (< 0.5 Ω).
- A very large and/or extensive ground grid.

Noise can be a significant issue when testing grounding systems. Noise may exist in a number of ways, including:

- Residual ground grid current (unbalanced loads)
- Third and higher order harmonic currents flowing in the ground grid
- Induction into grounding conductors and metallic objects (fences) from nearby HV lines
- Induction into test leads from nearby HV lines

Most portable ground testers use a low current (< 50 mA). Higher levels of current are required to distinguish between the test signal and any unwanted noise. Ground grid testing by current injection is used where portable ground testers are unsuitable.

Current injection at the fundamental frequency is one example. Provided the current is high enough then any noise on the system may be swamped. However, this is not usually a practical option since a significant power source is required (such as a power station generator). This method has the advantage that traditional RMS wide band multimeters can be used.

Finally, a particularly useful technique involves injecting current into the grounding system at a frequency close to the power frequency (known as off-frequency injection). A unique test frequency is chosen so that any voltages measured at this frequency must be created by the test current. This technique is explained further in the following sections.

5 Off-Frequency Injection Testing

This method offers a number of advantages over other methods, provided suitable test equipment is available.

Grounding systems frequently have residual voltages on them, caused by unbalanced loads, electrostatic and electromagnetic induction. Similarly, when testing grounding systems, the test leads may have significant induced voltage and current in them. The voltages will be at the power system fundamental plus harmonic frequencies.

Off-frequency injection using a unique signal is a practical and reliable method of discriminating against these interference signals. Off-frequency injection allows identification of relatively low signal levels against much higher background noise levels. As an example Figure 1 below shows the grounding system voltage rise and injection current measured during injection testing of a 50 Hz power system ground grid. The top trace shows the large amount of power system frequency noise present on the grounding system in addition to the injected signal (58 Hz in this case).

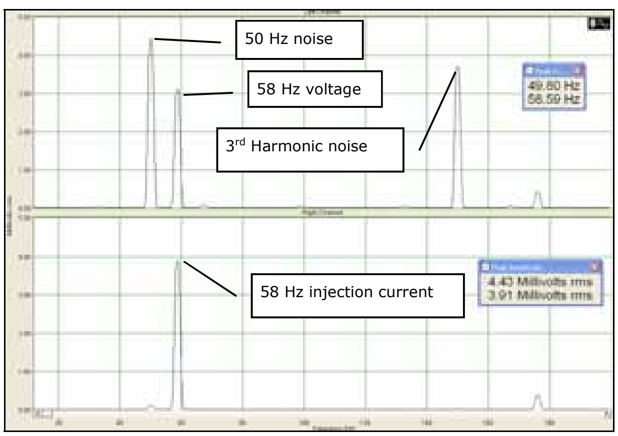

Figure 1: Background power system noise

Off-frequency injection testing has many possible applications. New grounding systems will generally have been well designed using software such as CDEGS™. Upon completion of the construction, injection testing can be carried out to confirm the design.

Existing grounding systems, particularly large systems, unless they have been designed well, may present ground potential rise hazards. These systems are often difficult to model since the existence and location of all metallic conductors may not be known. For example, on a power station, there may be fences, fire hydrants, water and gas supplies that are not easily identified or able to be incorporated into the model. Sites may also have been modified without reference to the grounding system integrity and the information not recorded on drawings (e.g. new security fencing). Injection testing provides a reliable method of ensuring correct operation of existing grounding systems where modelling is too complicated and/or infeasible.

5.1 Test Method

5.1.1 Current Source

The test current can be obtained from a diesel generator or a portable solid state injector such as the LCI-2052 (Mitton Instruments Ltd). Diesel generators provide a constant voltage output and can be a disadvantage where the remote ground is comprised of driven ground rods. If there is sufficient current, the driven rods will heat up and dry out the surrounding ground leading to an increasing resistance. The test current will therefore decrease over time. A constant current level is required to ensure that voltages measurements are consistent for the duration of the testing.

Table 1 below gives a general comparison between using the LCI-2052 solid state injector and traditional generator based testing.

Diesel Generator	LCI-2052
Generator must be frequency adjustable.	Frequency locked (52Hz).
Constant voltage. Injection current may decrease over time due to heating of driven rods.	Constant current. Remains constant even if injection circuit impedance varies.
Suited for very large grounding systems and/or where induced currents exist in injection circuit.	Tolerates limited induced current. Suited to small-medium ground systems.
Heavy.	Portable.

Table 1: Current injection equipment comparison

The test current can typically be in the range of 2 A to 100 A. Higher current will provide higher voltage measurements. Higher currents, using a diesel generator, may be required for large grounding systems where the grounding system voltage rise will be low.

5.1.2 Test Frequency

A test frequency close to the power system fundamental frequency is used. This means that the characteristics of the grounding system can be determined without the need to compensate for higher or lower frequencies. (A small correction factor can be applied if the grounding system has significant reactance).

A frequency between 50 Hz – 60 Hz is recommended especially where a diesel generator is used. Most diesel generators can be adjusted between 50 Hz – 60 Hz.

For 60 Hz systems, a test frequency of 52 Hz is used. (For 50 Hz systems a frequency of 58 Hz is used). There are two reasons for this. The first is that it is a unique signal and it is almost impossible for 52 Hz or its harmonics to exist on a 60 Hz system. If the 52 Hz signal is detected anywhere on the grounding system then it must be a result of the 52 Hz injection current. The second reason is that it is practical to design a narrow-band tuned voltmeter at this frequency (but is more difficult as the frequency gets closer to the power system frequency).

5.1.3 Injection Circuit

The injection circuit can comprise either an out-of-service distribution or transmission line or an independent cable. The basic injection circuit is shown below in Figure 2.

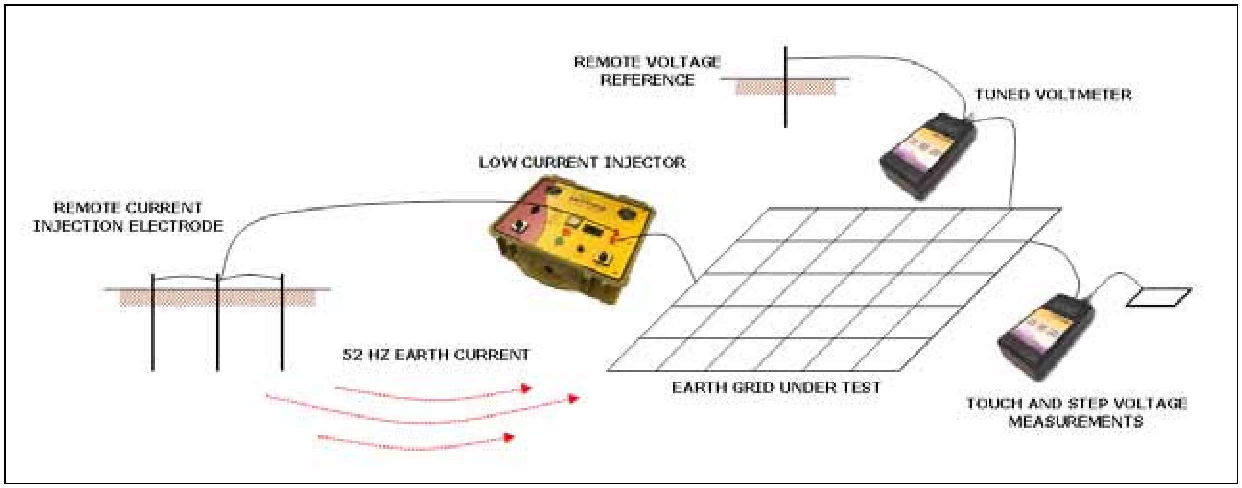

Figure 2: Typical Off-Frequency Current Injection Circuit

An out-of-service line is convenient if available. The line is connected to ground at its remote end or part way along. However, caution is required since any nearby lines may induce significant relative currents in the line being used for testing. In some cases the injection equipment will need to be adequately rated to carry the test current plus any induced current.

If an out-of-service line is not available, then an independent cable can be run out from the grounding system under test. The length of this cable should be at least six times the diagonal length of the grounding system under test.

CDEGS™ can be used to predict the minimum distance that the remote ground should be located. CDEGS™ can also be used to provide the approx percentage error that will arise due to the location of the remote ground.

5.2 Impedance Measurements

To correctly determine the grounding system impedance, the voltage rise of the ground grid must be measured with respect to remote ground.

An effective way to determine to ground grid voltage rise is to perform a GPR 'traverse'. This enables ground surface voltages to be determined and also the maximum GPR of the grounding system under test. The simplest method is to record the voltage between the grounding system and the ground at regular intervals using the tuned voltmeter. Readings at 1, 2, 3, 4, 5, 10, 20, 50, 100, 200, 300 m and greater are typical. As the distance increases the rate of increase in GPR will decrease until the readings are relatively constant (see Figure 3 below). This indicates that "remote" ground has been reached. The GPR graph can be extrapolated if necessary.

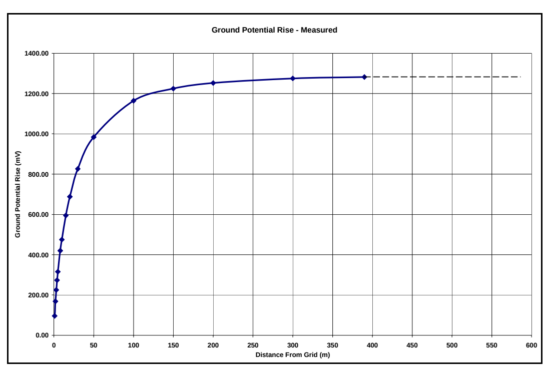

Figure 3: GPR Graph - Measured

The GPR traverse should be carried out as close as possible to 90° to the injection current route. This minimises any induced voltage in the traverse cable caused by the injection current. This is very important where the grounding system impedance is less than 0.5 Ω otherwise significant errors in the impedance will arise.

In some cases it may be possible to obtain a separate remote ground reference from the local telecommunications company. This provides a useful check on the "remoteness" of the traverse.

The grounding system voltages arising from the low current injection method can be relatively low (down to mV for low impedance systems). This means that a wide band voltmeter cannot be used since any power system noise on the grounding system or in the test leads will result in additional voltage which can lead to significant errors. A narrow-band voltmeter with a high degree of 60 Hz rejection is required. The TVM 1052 (Mitton Instruments Ltd) has these characteristics.

The maximum test GPR divided by the test current yields the impedance of the grounding system. Some grounding systems may have a significant reactive component caused by OHEWs and cable screens as well as long buried conductors. In such cases the phase angle between the voltage and current may be of interest. A dual channel spectrum analyser can be used to identify these components.

5.3 GPR and Telecommunications

The ground potential rise (GPR) arising from real power system ground faults is also of particular importance to telecommunication companies. If high enough, the rise in potential of the ground can cause insulation breakdown and other damage to nearby telecommunication cabling and equipment. In addition to this, the GPR can create hazards for technicians working on the affected circuits. The GPR traverse measurements can be used to gauge the severity of the GPR encountered during a real power system ground fault.

If the graph in Figure 3 is replotted with respect to remote ground then the actual ground surface GPR can be seen. If this plot is then scaled up by the ratio of the real fault current to the test current then the true GPR is found (see Figure 4)

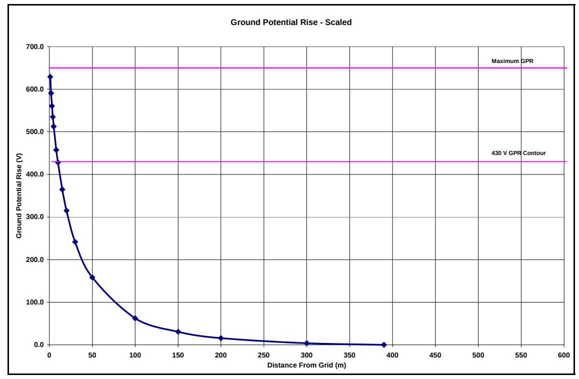

Figure 4: True GPR Graph

From this, GPR contour locations of interest can be identified. For example, the 650 V contour may be of significance to telecommunications companies.

Using a grounding system software package such as CDEGS™, the GPR traverse measurements can be used to create a measurement based GPR contour plot. The known ground grid dimensions are modelled then the soil resistivity is adjusted to recreate the GPR contour locations and impedance found during injection testing (see Figure 5).

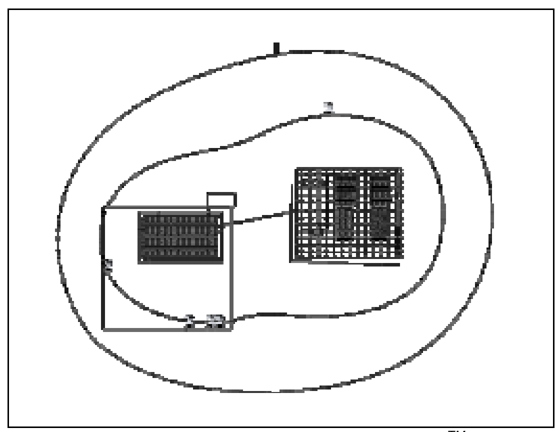

Figure 5: GPR Contour Plot (CDEGS™)

5.4 Touch and Step Voltages

Touch voltages are identified by measuring the voltage between the metallic item under test and the ground surface 1 m away. A probe or metal plate is used for the ground contact. The touch voltages recorded are prospective values and the same as those produced by ground grid modelling software.

The prospective voltage is independent of the ground surface treatment or resistivity. This voltage is the same as that predicted by CDEGS™ modelling. If the same measurement is made with a 1,000 Ω resistor across the voltmeter, an indication of the actual touch voltage that may appear across a person's body is measured. With the resistor loading the touch voltage source, the touch voltage will reduce depending on the surface contact resistance with the metal plate.

For example, a prospective touch voltage reading of 500 mV on a crushed rock surface may reduce to 20 mV when loaded with the resistor. This indicates the beneficial effect of a crushed rock layer. In contrast, a prospective reading of 500 mV on natural soil may only reduce to 400 mV when loaded with the resistor, indicating the good contact (low series impedance) with the soil. The TVM 1052 includes a switchable 1,000 ohm resistor to enable this test to be easily carried out.

Figure 6: TVM 1052 Tuned Voltmeter

Figure 7: Touch Voltage Measurement

Step voltages are measured in a similar way but using two probes or metal plates spaced 1 m apart.

Figure 8: Step Voltage Measurement

The measured touch and step voltages are then scaled up to represent a real fault situation. The current injection method directly simulates a real fault situation. Therefore the measured voltages can be directly scaled by the ratio of the test current to the worst case fault current. The scaled touch and step voltages can then be compared to tolerable limits given by IEEE80 [3] or similar electrical safety standards.

The IEEE provides guidelines for calculating touch and step voltage limits based on restricting body currents to safe levels defined by C.F Dalziel in 1946 [4]. As reflected in the equations, the current in the shock path is limited by the human body impedance and the contact resistance between the person and the ground.

It is well documented that the contact resistance of a foot on the ground is proportional to the surface soil resistivity [5]. This means that the allowable touch and step voltage limits are higher for high resistivity surfaces such as asphalt and crushed rock. Problems are encountered on low resistivity surfaces such as wet concrete and natural soil where the contact resistance is low and body currents can be high. Testing for touch and step voltages should be concentrated in these problematic low resistivity areas.

The loaded touch and step voltage measurements can also be used to calculate the surface soil resistivity. The following formula gives the resistivity based on the loaded and prospective touch voltage measurements:

$$\rho_{Surface} = \frac{1,000\left(V_{Prospective} - V_{Loaded}\right)}{1.5V_{Loaded}}$$

A similar formula can be derived based on step voltage measurements:

$$\rho_{Surface} = \frac{1{,}000\left(V_{Prospective} - V_{Loaded}\right)}{6V_{Loaded}}$$

The above formulae apply for low impedance grounding systems (<50Ω) where the 1 kΩ load does not effect the overall grounding system voltage rise. A number of calculated resistivity values can be averaged to determine the most likely surface soil resistivity.

5.5 Current Splits

The current injection method enables the effect of additional grounding paths such as cable screens and overhead ground wires to be determined. The off-frequency current in these conductors can be measured using a flexible current transformer (CT) and a tuned voltmeter. Only the test current will be measured as the tuned voltmeter blocks out any power frequency signals. This means that the CT can be put directly around three phase or single phase cables to measure only the 52 Hz test current in the cable screen.

Figure 9: Cable screen measurement

Test current can be detected in almost any conductor such as buried services (water pipes etc), overhead ground wires, cable screens, telecommunications circuits, gas pipelines, and LV neutrals. Testing is only limited by what the CT loop can fit around.

The measured currents can be scaled up to the real fault situation. This gives an indication of the likely current that will flow in these additional grounding paths during a fault.

6 Additional Applications

There are also other uses for off-frequency current injection methods. For example, induced voltages into nearby telecommunications circuits running parallel to a power line can be measured. The screening effects of OHGWs and other metallic objects can also be checked. By injecting the unique 52 Hz test signal, the effect of individual sources can be distinguished from background sources.

7 Grounding System Software

The results of testing can be combined with computer modelling to produce a realistic understanding of the grounding system. Modern grounding system software such as CDEGS™ allows comprehensive grounding models to be created based on grounding system dimensions and soil characteristics.

The model can then be used to investigate changes to the grounding system and identify any possible hazards (such as touch and step voltages, GPR issues etc). Mitigation options are also easily analysed should hazards exist.

8 Conclusions

The paper has detailed the theory behind and practical applications of current injection testing of grounding systems. Current is injected at a unique frequency to distinguish the test signal from background noise. Tuned voltmeters are used to measure both the grounding system voltage rise and voltages differences around the site cased by the ground potential rise.

From these measurements the overall grounding system impedance can be determined and touch and step voltages can be identified and analysed for site safety. The system voltage rise is also valuable for producing ground potential rise information that is required by telecommunications companies.

More specialised applications are also possible such as investigating induction into nearby services from power lines and resistivity testing.

Power utilities can cost effectively monitor the operation of grounding systems by performing regular injection tests. The test method is simple to perform and the equipment is reliable and portable. In this way site safety can be assured by easily identifying hazards following direct or indirect changes to a grounding system such as the addition of equipment or changes in security fencing that may present touch voltage hazards.

The current injection method also goes hand in hand with computer modelling of grounding systems such as that enabled by CDEGS™. By testing after construction of new or modification of existing grounding systems, direct feedback is achieved in the design process. The theory of grounding is often not well understood and testing provides a valuable feedback tool for the engineer to assist with the design of grounding systems.

Off-frequency current injection provides a practical and reliable way to test and evaluate the characteristics of a grounding system and overcomes the shortcomings of traditional grounding system testing methods.

9 References

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